Design Criteria for Avalanche Control Structures in the Runout Zone

Arthur I. Mears

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Abstract

Guidelines are given for the design and location of deflecting, catching, retarding, and direct protection structures. Terrain, snow conditions, and type and frequency of avalanches are among the most important criteria for planning structural control of avalanches in the lower track and runout zone.

The cover: Earth mounds covered with snow in Glacier Park, Canada. (photo by Peter Schaerer of Vancouver, British Columbia)

Photographs not otherwise identified are by the author.

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INTRODUCTION AND GENERAL INFORMATION

Encounter Probability and Land Use

When land use or proposed land use conflicts with the natural avalanche condition, and the encounter probability of an avalanche reaching man and/or his works is sufficiently high, avalanche defenses are essential. The encounter probability E can be computed given knowledge of the avalanche-return period T in the area of interest and the length of time L that this area will be occupied (LaChapelle 1966). Thus

$$E = 1 - (1 - 1/T)^L \quad [1]$$

The return period is the reciprocal of the probability that the avalanche will occur during any given year. If, for example, an object is to be located for 30 years at a spot expected to be reached by avalanches once in 50 years on the average, then the probability of the object being reached once by the avalanche during this or any other 30-year period is 0.45 (eq. [1]).

The acceptable value of E is a matter of opinion. In Alta, Utah, for example, computation of E is not made, but private land owners are building new structures where avalanche encounter is a virtual certainty, at Ketchum, Idaho, and Vail, Colo., local authorities consider acceptable only much lower encounter probabilities. Figures 1, 2, and 3 illustrate avalanche-hazard areas. The individual accepting the risk, or the government body controlling land use, must determine what level of risk is acceptable.

If the encounter probability exceeds limits set by individual or government decisions, then the risk is not tolerable, and construction within the avalanche zone should be reduced by prohibiting or limiting construction or by protecting structures through the use of avalanche defenses. Several types of defenses which have been used are discussed briefly in this report.

The design-avalanche concept should be used in planning. A design avalanche is of a magnitude such that it will occur once, on the average, in a period of T years. Thus a design avalanche has an annual probability of $1/T$. The annual occurrence probability does

Figure 1.—These small avalanche paths threaten new buildings at Vail, Colo. Although the paths are small and located in the timber, avalanches are known to have reached the sites of the buildings. The duplex on the right is designed to resist flowing-avalanche impact.

not change after an event occurs; therefore, design avalanches are possible on successive years, or even more than once during a single year. Selection of a return period T depends upon the type of facilities exposed, but usually varies between 50 and 300 years.

Types of Avalanche Defenses

Several types of avalanche defenses are possible. A decision about what type or types are most appropriate in a given situation should be based on several factors, including the following:

The Type and Intensity of Hazard

The methods used to reduce avalanche hazards depend to some extent on whether mobile or fixed objects are threatened. When mobile objects such as automobiles, railroad trains, and skiers are exposed to severe conditions only occasionally, the hazard can often be reduced by restricting the use of the highways, railroads, or the threatened parts of the ski areas until the avalanches can be released artificially by explosives. This reduces the possibility of damage or injury. Such procedures are common but are not highly reliable in all cases. Effective control requires detailed knowledge of the snowpack, which is not always available to personnel conducting the control operations. Nevertheless, it is possible to remove skiers, automobiles, railroad trains, and other endangered objects while control attempts are made.

Artificial release is usually an unacceptable control alternative for eliminating the hazard to immovable objects such as buildings, bridges, or tunnel portals, because avalanches released in this manner may be larger than expected and can destroy the unprotected structures. Because these objects cannot be removed during times of avalanche occurrence, it must be assumed that natural avalanches which are unmodified by defense structures will reach the objects, given a long enough time period L. If the encounter probability E is sufficiently high, structural control should be used for protection.

Two broad categories of avalanche-defense structures have been used—supporting structures in the starting zone and deflecting or diverting structures in the track or runout zone. The objective of supporting structures is to prevent, or to limit, the size of avalanche release. Supporting structures anchor the snow to the mountain and alter the stress and deformation within snowslabs. They are designed primarily for static loads resulting from creep and glide of the snowpack and the small dynamic loads resulting from small slides between the structures. The Swiss have gained considerable experience in the design, construction, and maintenance of supporting structures and have developed engineering guidelines for their construction (Swiss Federal Institute for Snow and Avalanche Research 1961). Design of supporting structures will not be discussed in detail in this publication.

Figure 2.—Severe (but infrequent) avalanche hazard exists in the Warm Springs area of Ketchum, Idaho. Avalanches are known to have traveled 100-200 m out onto the valley floor. Although this is a good location for certain types of avalanche defenses, there has been no systematic attempt to mitigate the avalanche hazard.

Figure 3.—Large avalanches are known to cross Little Cottonwood Canyon near Alta, Utah, every few years. Buildings and automobiles have been damaged by avalanches in the past. In the future, builders will probably design any new buildings located within designated avalanche paths to resist avalanche impact.

The second type of defense structures are designed to withstand the forces resulting from moving avalanches. These structures are built in the track and/or runout zone (parts of the avalanche path are defined in the next chapter). Several types of track and runout-zone structures are possible, depending on several factors as discussed below.

Avalanche Path Terrain

Avalanche terrain is the first factor affecting the design of structures in the track or runout zone. It is discussed in more detail in the section entitled Design Criteria because it relates to avalanche size and motion; however, designers should ask the following basic questions prior to deciding on the appropriate type of defense:

Are many valuable objects exposed in the runout zone (the location in which avalanches decelerate and stop)? If so, it may not be possible or practical to stop or deflect the flow. Rather, it may be necessary to use supporting structures to prevent or limit the size of the avalanche.

Is the starting zone (the location in which avalanches begin and accelerate) small and well defined? If so, avalanches may be most efficiently prevented by use of supporting structures.

Is the starting zone large but the runout zone long and gradual? If this is the case, it may be possible to dissipate avalanche energy or deflect the flow in the runout zone, thereby protecting some objects.

Is the track confined to a channel or is it unconfined? Confined tracks often discharge onto alluvial fans. Irregularities on the fan surfaces may provide natural barriers to flow, or it may be possible that natural barriers can be enlarged to deflect the flow away from objects.

Economic Feasibility

Early planning and identification of potentially hazardous areas may allow development to avoid avalanche areas completely. In these cases, complete avoidance may be the best and most economical form of defense (fig. 4). However, landowners may not feel this is a viable alternative, based on real estate values. If a decision about whether or not to build avalanche defenses is to be made on purely economic grounds, then it may be useful to compare the cost of defenses to the benefit obtained. Annual cost can be computed by amortizing the initial cost of defense over some time period, such as the life of the structure. Assuming an interest rate, the annual cost can be computed (see Taylor (1964), for example). The benefit would be equal to the annual cost of avalanche damage avoided by construction of the defenses, and is equal to the ex-

pected cost of damage times the annual probability of avalanche occurrence. Thus, the benefit/cost ratio, BCR, can be computed

$$\text{BCR} = \frac{\text{annual benefit}}{\text{annual cost}} = \frac{\text{cost of damage avoided}}{\text{amortized construction cost}}$$

Although a benefit/cost analysis may be a rational way to make economic decisions about construction of defense structures, important but less quantifiable factors may be equally important. An unprotected structure in an avalanche zone may be damaged by impact so severely that the occupants are injured or killed. Thus, even if construction of defenses appears economically unfeasible, defenses may be desirable.

Types of Avalanches Expected

The design of structures also depends on the type of avalanche expected. This factor will be discussed in detail in the section on Design Criteria. Certain types of defenses will not be effective against some avalanches. For example, a deep, powder avalanche cannot be stopped or deflected by a low, catching dam or deflecting wall (see sections on Deflecting, Guiding, and Catching Structures). If large, powder avalanches are expected to reach the design point in the avalanche path, then reinforcement of the object may be the only viable type of defense.

Esthetic Considerations

Because avalanche defense structures may have an adverse effect on the environment, esthetic considerations affect the design of control structures. As discussed later, earthen structures need to be quite massive. In some cases, this requires extensive earthwork. Such construction may have an undesirable visual impact and may create new erosion patterns. Early in the planning, designers must give careful consideration to any development in hazardous areas if such development requires avalanche defenses that have an undesirable environmental impact.

In contrast, direct-protection features may be incorporated into the design of structures. Careful architectural design can result in structurally sound buildings with no undesirable visual impact (fig. 29 in the DIRECT-PROTECTION STRUCTURES section). However, for reasons discussed in the section on Direct Protection Structures, direct-protection structures are not always a viable form of avalanche defense.

With all the necessary information about alternative types of defenses at hand, the designer can decide which types of defenses are most suitable at a given site. If track and runout-zone defenses are most suitable, then the designer of the defense must accumulate the necessary design data. This procedure involves calculating the dynamics of the design-magnitude avalanche as discussed in the section on Design Criteria.

Figure 4.—The village of Monbeil, near Klosters in the Swiss Alps, has been located out of the path of the design avalanche as evidenced by the patch of mature trees above the village. In this case, avalanche mitigation is achieved through avoidance.

Analytical Techniques, Uncertainties, and Limitations

Throughout this paper, suggested design techniques are based upon the characteristics of avalanches and other factors. The material presented is based on basic fluid mechanics applications, measured properties of avalanches contained in published or unpublished reports, equations proposed in previous work and introduced in this paper, and experience gained in the field concerning the behavior of avalanches and control works. Some of this experience has not been verified quantitatively.

A case in point concerns the computations of design avalanche velocities and runout distances, two parameters of prime importance in avalanche zoning and structural design. Voellmy (1955) first introduced a modified fluid-dynamic basis for computing avalanche velocity and runout distance. The theoretical validity of this approach has since been questioned by Salm (1966), by Lang and others (1979), and by Perla and others (1980). However, none of these more recently proposed methods has been calibrated with field observations of design-magnitude avalanches any more successfully than the procedures first proposed by Voellmy (1955). The field calibrations that have been used to test new methods (Lang et al. 1979, Perla et al. 1980) have not reduced the subjectivity inherent in selecting important coefficients used in the computation of velocity and runout distance.

Given all the uncertainties that remain regarding the methods for computing avalanche dynamics, we present the simple method first proposed by Voellmy (1955), as modified by recent observations (Sommerhalder 1978, Martinelli et al. 1980). The Voellmy technique still represents the state of the art in avalanche-dynamics technology as well as any other.

DESIGN CRITERIA

Definition of the Design Criteria

The term "design criteria" refers to the physical characteristics of the avalanche that must be considered when specifying defense structure position, orientation, size, strength, and material. The following avalanche characteristics must be known in order to provide the proper design:

- Avalanche type (wet or dry snow, loose snow, or slab),
- Type of avalanche motion (powder, flowing, or mixed),
- Avalanche velocity (the mean velocity at the front of the avalanche),
- Avalanche flow height,
- Avalanche flow density,
- Avalanche discharge (mass per unit time at some location),
- Avalanche impact or stagnation pressure,
- Avalanche deposit volume, and
- Number of avalanches per winter.

These characteristics are obtained through field observations at the area of interest, comparison of this area with other avalanche paths of known characteristics that are located in a similar climate and have similar orientations, terrain configurations, and sun exposures, and through application of equations.

Avalanche researchers recognize that none of these characteristics can be specified with a high degree of precision because we are only learning about avalanche dynamics through present research efforts. Nevertheless, it is essential that we make use of the body of knowledge as it exists today. The fluid-mechanics models of avalanches used most commonly today in Switzerland, Austria, and the United States are crude approximations to a complex, natural phenomenon. In time, more data will be collected, measurements will improve, and perhaps new experiments will be carried out which will affirm, modify, or negate the present model. In the meantime, realizing that the results of the present model are only approximate, land-use planners and designers must make decisions through application of the present state of the art in avalanche dynamics. This is a normal procedure in science and engineering; and, if the procedure is allowed to operate, it will gradually provide improved models upon which more accurate estimates of the magnitude of the design avalanche can be made.

Few data on avalanche velocity, dynamic pressure, density of flow, or length of travel (runout distance) have been obtained with which to advance a single coherent model of avalanche motion or impact. However, research suggests that avalanches tend to behave as fluids or, when velocities exceed roughly 15 m/s, as high-velocity, density currents.[2]

Information Necessary for Structure Design

In order to design structures to withstand, deflect, or stop moving avalanches, we must have information about the following: the total static and dynamic force on the structure, the required size (height, width, and length) of the structure, the volume of avalanche debris in the deposition area, or in the area where the structure will be built, and knowledge of any change in the avalanche direction as a result of the defenses.

This information can only be obtained through analysis of the design avalanche and determination, through calculation, of the avalanche characteristics discussed previously.

Calculation of the Design Avalanche Dynamics

Previous Work

Voellmy (1955) derived the fluid-dynamic basis of snow avalanche motion and impact. His original equations have been modified through subsequent research,

[2] *Data in files of Arthur I, Mears, P.E., Inc., 222 E. Gothic Ave., Gunnison, Colo. 81230, 1980.*

but the basic equations and assumptions of Voellmy are widely applied in Austria, Switzerland, Canada, and the United States.

Sommerhalder (1965, revised in 1971 and 1978) summarized the avalanche dynamics equations commonly applied in the Swiss Alps.

Mears (1976) presented various methods for computing and otherwise determining avalanche hazard through analytical and observational methods.

Leaf and Martinelli (1977) summarized the state of the art in avalanche dynamics equations as developed in the preceding 22 years.

Perla (1980) summarized avalanche release, motion, and impact from a theoretical and practical standpoint.

These publication should be consulted for details on computational techniques and for the theoretical justifications of various assumptions used in computations. A short summary of some of the more important techniques follows.

Dynamics of Flowing Avalanches

Flowing avalanches (from the German *fleisslawine*) refers to the type of motion where most of the mass slides, flows, and bounds within 2 to 5 m of the ground. Although the analytical techniques discussed below assume an avalanche is a continuous, incompressible fluid, it should be remembered that real avalanches consist of fragments of the slab. These fragments may range in size from finely pulverized snow to chunks more than 1 m in length. A hard-slab release may produce an avalanche that is a cascade of large slab fragments and does not resemble a fluid, while a soft-slab avalanche may become quickly pulverized into small fragments suspended by air turbulence. In the first case, a fluid model may be inappropriate (fig. 5) while in the second case, it may be acceptable (fig. 6 and 7).

According to the fluid-dynamic theory, which has been adapted from empirical studies of water flow in open channels, the maximum velocity of a flowing avalanche is computed as

$$V = [\xi h' \, (\sin \alpha - \mu \cos \alpha)]^{1/2} \qquad [2]$$

where h' is the flow height, ξ is a turbulent friction coefficient, μ is a sliding friction coefficent at the base of the avalanche, and α is the slope angle. In practice equation [2] is usually applied several times over a long avalanche path of complex topography and varying longitudinal gradients. In each case $\xi h'$, μ, and α will have different values depending upon slope, roughness, and entrainment of new snow into the avalanche.

Table 1 provides estimates of the parameters of equation [2] based on a synthesis of field work conducted in the United States and Canada (Schaerer 1973, Martinelli et al. 1980). The flow height h' is given as a multiple of the mean fracture height h_0; both h' and h_0 are measured perpendicular to the avalanche running surface.

In the original Swiss work (Voellmy 1955, Sommerhalder 1965), it was assumed, for unconfined avalanches, that the flow height of the avalanche, h', was approximately equal to h_0, the height of the released slab. However, recent research in the United States[2] suggests that dry, soft-slab avalanches disintegrate

Figure 5.—This hard slab avalanche consisted of large fragments. In such cases a fluid-dynamic model of avalanche motion is not appropriate.

and disperse upward after a short running distance. Thus, it is not justifiable to assume $h' = h_0$. Typical values of the ratio h'/h_0 are related to avalanche type in table 1. In general, dry, soft-slab avalanches attain greater flow depths than dry, hard-slab avalanches, and larger, higher velocity avalanches attain greater flow depths than smaller, slower avalanches of the same type.

Prior to application of equation [2], the designer must determine the type of snowslab expected to be released from the starting zone during design avalanche conditions. This can be done from avalanche and meteorological records and through discussions with observers. (Examples of starting zones are shown in figures 8, 9, 10.) Variation in ξ and μ also strongly affect the computation of velocity. The smaller values of ξ apply when the avalanche falls through rough terrain with many trees and rock outcrops, and the larger values apply when avalanches run on smooth surfaces such as old avalanche debris. The range in μ varies by a factor of three in response to snow type, terrain, and possibly degree of slab fragment dispersion in the flow (Mears 1980). In general, μ is probably small in large avalanches and the product ξh is large.

The bulk density of a flowing avalanche should be proportional to h_0/h'. Thus, with $100 \leqslant \rho_0 < 300$ kg/m³, and $1.0 \leqslant h'/h_0 \leqslant 5.0$, the bulk density, ρ, of the flowing snow can range 20-300 kg/m³; ρ_0 is snow pack density. Bulk density probably decreases with distance from the ground in dry-snow avalanches, and the mean forward velocity probably increases with distance above the ground. For design purposes, it is probably acceptable to assume a uniform density of 100-200 kg/m³ for dry-flowing avalanches throughout the depth of flow. The larger value should be assumed for smaller, lower velocity avalanches, and smaller values for higher velocity avalanches.

Avalanches decelerate and stop in the runout zone as the kinetic energy of flow is gradually dissipated through friction over some distance S known as the runout distance. Equating kinetic energy to work done through flowing and sliding in the runout zone yields Voellmy's (1955) expression for runout distance

$$S = \frac{V_0^2}{2g(\mu \cos\beta - \sin\beta + V_0^2/2\xi h')} \qquad [3]$$

where V_0 is the velocity at the beginning of the runout zone and β is the mean slope of the runout zone. For large, dry-snow avalanches, it should be assumed that the runout zone begins when the slope angle decreases to 15-20°. Such avalanches may run for 1,000 m or more on slopes of 10° or less. However, selection of a reference position for the beginning of avalanche deceleration is sometimes difficult and subjective, particularly in avalanche paths with gradually decreasing longitudinal gradients. The beginning position of deposition is thought to correspond to the beginning of final deceleration (Mears 1980).

If wet-snow avalanches are known to be the design case, then flow work will not be an important energy-dissipative mechanism in the runout zone and may be

Table 1.—Suggested values of coefficients used in equation [2]

Avalanche type	ξ	h'	μ
	m/s^2		
Thick, hard slab	400-600	$h_0 - 2\ h_0$	0.15–0.30
Soft slab	400-1,000	$1.5\ h_0 - 5\ h_0$	0.10–0.30
Wet slab	400-600	$h_0 - 2\ h_0$	0.10–0.20

Figure 6.—Most of the flowing mass of dense snow in this mixed motion avalanche is obscured beneath a deep, diffuse cloud of small snow and ice particles. (Schoolhouse Avalanche near Camp Bird, Colo. Photo by Johnny Johnson Petley Studios, Ouray, Colo.)

disregarded in equation [3] provided $V_0 < 10$ m/s. Thus, the runout distance for wet-snow avalanches, S_w, is computed simply as

$$S_w = \frac{V_0^2}{2g(\mu \cos \beta - \sin \beta)} \quad [4]$$

Equations [3] and [4] should be applied only when $\mu > \tan \beta$. In contrast, when $\mu < \tan \beta$ and $S_w < 0$, the avalanche is still in steady flow and will not stop in that section of the path.

Often avalanche defense facilities will be planned within the runout zone. For the proper design of such structures, the designer must determine the avalanche velocity at some point within the runout zone. If total frictional work against the flow is assumed constant across the runout zone, then it may be assumed that the dissipation of kinetic energy is constant with distance traversed. From these assumptions we can determine the velocity, V_x, at some point a distance, x, into the runout zone as

$$V_x^2 = V_0^2 \, (1 - x/s) \quad [5]$$

Analysis of Channelized Avalanches

Channelized avalanches require a different method of analysis because the snow released in the starting zone is laterally confined in the track and one can no longer analyze motion on a per-unit width basis. Field observations suggest that the flow height h' within channels below large starting zones is substantially larger than those suggested in table 2 for nonchannelized avalanches. In such observations, however, it is difficult to distinguish powder-blast damage (discussed below) from flowing avalanche damage; thus, results obtained through application of equations [6]-[10] should be considered approximations. Usually, flow

Figure 7.—A wet-snow avalanche moves slowly and has a smaller flow depth than large, dry-snow avalanches. The direction of wet-snow avalanches can be changed because of their moderate velocities (photo taken near Davos, Switzerland, by Andre Roch of Geneva).

Figure 8.—The smooth, and broad starting zone of this avalanche path is above timberline. During design-avalanche conditions, a large slab may be released from the entire starting zone. (Glory Hole Avalanche, near Wilson, Wyo.). Photo by Hans Frutiger.

depths and velocities are larger and runout distances are greater when a given volume of snow flows down a channelized track than when it flows down an unconfined slope.

Figure 11 illustrates a channelized avalanche path below a large starting zone. A large release of snow of volume K in the starting zone will produce a large discharge rate Q in the track where the flow is confined. It is assumed that the mean discharge from the starting zone equals the mean discharge through the confined section of the avalanche track. If the discharge in the track is large, this forces the flow height and hydraulic radius to be large also. For the channelized avalanche case, the flow depth h' in equation [4] should be replaced with the hydraulic radius R so that the terminal velocity becomes

$$V^2 = \xi R(\sin \alpha - \mu \cos \alpha) \qquad [6]$$

Equation [6] indicates that the terminal flow velocity is proportional to the square root of R. The term $(\cos \alpha)^{1/2}$ varies by only a small amount across the range of slopes on which large avalanches occur (Bovis and Mears 1976), and the term $(\mu \cos \alpha)^{1/2}$ may become insignificant at high velocities.

The physical dependence of R on starting-zone area is best illustrated by combining equation [6] with the continuity principle of hydraulics. For a given starting-zone area A and height of released snow slab h_0 the volume K of snow released is

$$K = Ah_0 \qquad [7]$$

As discussed by Salm (1975), the volume K is completely discharged through the starting zone when the upslope margin of the detached slab has traversed the slope distance L measured from the top to the bottom of the starting zone. The time required to discharge the slab from the starting zone is

$$t = L/V \qquad [8]$$

and the mean discharge rate during this time, t, is

$$Q = K/t \qquad [9]$$

Continuity requires that this Q also be conveyed through the channelized track if it is assumed that deposition and entrainment within the track are equal. Within the track

$$Q = A_t V_t \qquad [10]$$

where A_t is the track cross-sectional area at a given point, and V_t is the average flow velocity through this cross section. Because A_t and R are related through

cross-section shape, and V_t is a function of R from equation [6], equations [6] and [10] must be satisfied simultaneously, specifying both cross-section area and avalanche velocity through a given cross section.

An accurate estimate of the starting-zone area A and the release volume K is critical in an analysis of this type. Observations of large avalanches (Mears 1980) suggest that there be net removal of snow on slopes of 30° or steeper, and that deposition and entrainment of new snow become approximately equal on slopes of 20-30°. Thus, for purposes of design, it should be assumed that the starting zone (the area of the avalanche path contributing to K) consists of all slopes steeper than 30° that can release during design-avalanche conditions.

Powder Avalanche Dynamics

Powder avalanches are deep, high-velocity, low-density suspensions of small snow and ice particles in air. They result from disintegration of dry snow slabs and often accompany high-velocity, dry, flowing avalanches. Powder avalanches can form readily when dry, flowing avalanches fall over cliffs and additional air is entrained into the flow (fig. 12).

Powder avalanches are likely whenever the maximum velocity of dry, flowing avalanches exceeds roughly 30 m/s. At high velocity, energy dissipation within the flow causes larger chunks of the slab to become progressively fractured into smaller and smaller particles until a density current of snow mixed with air accompanies the denser mass of flowing snow. In this way, a powder avalanche becomes separated from the flowing avalanche, attains higher velocity, and reaches the runout zone several seconds prior to the main mass of the avalanche. At such high velocities and flow depths, powder avalanches will flow much longer distances into the runout zone than flowing avalanches.

It should be assumed that powder avalanches can form and be a part of the design-avalanche condition wherever moderate to large flowing avalanches can be expected. Following the definition of Frutiger (1964), medium-sized avalanches have starting zones of from 3×10^4 to 12×10^4 m^2 (7-30 acres). Large starting zones may, during favorable conditions, produce dry avalanches that move as flowing, mixed motion, or powder avalanches. This must be considered in the design of defense facilities.

Typical values of velocity, bulk density, and flow height for moderate to large, powder avalanches are given in table 2. The density values are only estimates, since no measurements have been made.

In an unrestricted runout zone (where runout distance is not limited by the opposite valley wall, for instance), it should be assumed that powder avalanches will travel considerably farther into the runout zone than flowing avalanches. It is not possible to compute the runout distance of powder avalanches. Some approximate guidelines can be given, however, to compare the runout distance of powder avalanches S_p with the runout distance S of flowing avalanches. As discussed earlier, S is computed through use of the methods discussed previously. These comparisons are valid only for the same avalanche path; thus, it is necessary to first compute or otherwise determine the flowing avalanche runout distance S and add to that the runout potential of the powder avalanche. Suggested differences between S_p and S are given below:

Avalanche size classification	S_p-S
Moderate	50–150 m
Large	150–300 m

Many avalanche runout zones are affected by both flowing and powder avalanches, which may be either wet or dry. Different types of avalanches can be expected to reach different parts of the runout zone (fig. 13).

Figure 9.—The starting zone of this avalanche path is below timberline. Even during design-avalanche conditions, much of the snow within the starting zone will remain anchored to trees and terrain irregularities. (King Arthur's Avalanche, Vail, Colo.)

Figure 10.—Avalanches on this unconfined avalanche path are known to have crossed the highway a distance of 350 m from the break in slope. In unconfined avalanche paths, the velocities and runout distances are not dependent on the width or area of the fracture. (Ironton Park, San Juan Mountains, Colo.)

Figure 11.—The velocity and runout distances potential of avalanches in this confined path depend partly on the volume of snow released from the starting zone. (Deadman Gulch near Silver Plume, Colo.)

AVALANCHE IMPACT

Knowledge of probable avalanche impact pressures is important in structural design. As discussed previously, fluid-dynamic models are commonly used in calculations of avalanche velocities and runout distances. Using this convenient simplification, avalanche impact can be modeled as the impact of a fluid with a stationary, rigid object. Such an assumption is justifiable for most avalanches, but it is important to recognize the limitations of this approach because of the variability of avalanche types, densities, velocities, and particle sizes.

Fluid Model

For an avalanche to be adequately modeled as a fluid, it is necessary for the snow and ice particles comprising the flow to be small, compared to the size of the impact area considered. Preliminary analysis indicates that a fluid-impact model is appropriate for powder avalanches and dry-snow avalanches in which most of the avalanche mass consists of particles less than about 10^{-4} m^3 in volume as long as the velocities exceed about 15 m/s. Most dry, soft-slab avalanches and powder avalanches satisfy these conditions; wet-snow avalanches and hard-slab avalanches probably do not. At velocities of less than 15 m/s, dry-snow avalanches may cease to flow as a fluid and begin sliding as rigid bodies. Thus, at low velocities, a fluid-impact model may not be accurate, as discussed below.

If an avalanche is modeled as a fluid of density ρ' moving at a velocity V, then the impact pressure P is determined by an expression of the form[3]

$$P = K\rho' V^2 \qquad [11]$$

where K is a dimensionless coefficient that depends on the details of the impact, the internal structure of the avalanche, and the shape of the object.

Powder Avalanche Impact

A fully developed powder avalanche usually moves at velocities exceeding 30 m/s and probably has a bulk density in the range of 2-20 kg/m³. Powder avalanche flow depth should be assumed to exceed 10 m, a depth sufficient to envelope an average sized, single-family dwelling. Because of this large flow depth and velocity, powder avalanches produce forces similar to those of a windgust of increased density. When a powder avalanche engulfs an object, a reference pressure, called the stagnation pressure, at the upstream face of the object can be computed by assuming $K = 0.5$ (eq. [11]). Stagnation pressure P_s is equal to

$$P_s = 1/2\ \rho' V^2 \qquad [12]$$

It must be remembered that P_s is only a reference pressure. To compute the design unit forces and total aerodynamic force on an object, P_s must be multiplied by the exposed area and by a coefficient of drag or lift. The total drag force F_d acts on the object in a direction parallel to the flow and is calculated

$$F_d = C_d A_d\ (1/2\ \rho' V^2) \qquad [13]$$

where A_d is the projected area normal to the flow and C_d is a coefficient which must be determined in-

[3]*Density ρ' has the units of mass/volume. In the SI system of units ρ' has the dimensions kg/m³. The unit weight, γ, is computed $\rho' g$ (kg/m² s²).*

Figure 12.—Cliff bands in the track of this avalanche path can transform moderately large, flowing avalanches into powder avalanches because of entrainment of air into the flow. (Waterfall Avalanche, Vail, Colo.)

Table 2.—Some powder avalanche characteristics

Size classification	Velocity range	Bulk density	Flow height
	m/s	*kg/m³*	*m*
Moderate	50–70	2–20	5–10
Large	70–100	2–20	10–20

Figure 13.—This avalanche discharge onto an alluvial fan. Wet slides in particular are deflected by ridges and gullies on the fan surface and can take unpredictable paths in the runout zone. However, dry-snow and powder avalanches tend to run directly across the fan. (Spring Gulch Avalanche, San Juan Mountains, Colo., photograph by Doug Wolfe of Ophir, Colo.)

dividually through an aerodynamic analysis of the structure. Aerodynamic studies show that, for large objects subject to loading from high velocity winds or powder avalanches, $0.5 < C_d < 1.5$. This range of values is only a rough estimate, but does indicate the wide range of values applicable to real structures.

The lift force F_1 is calculated

$$F_1 = C_1 A_1 (1/2\, \rho' V^2) \qquad [14]$$

where C_1 is the coefficient of lift. This coefficient must also be determined by an aerodynamic analysis of the structure. Generally, $C_1 < C_d$ for most structures which must be designed for the impact of powder avalanches. The area A_1 is the projection of the area of the impacted object on a plane parallel to the flow.

Numerical Example.—The design powder avalanche will be at least 15 m deep at the location of the building. Computations (see Design Criteria section) suggest that $V = 40$ m/s. Density is assumed equal to 10 kg/m³ throughout the depth of the powder avalanche. Application of equation [12] enables computation of a stagnation pressure

$$P_s = (1/2)(10)(40^2) = 8{,}000 \text{ kg/m}^2\text{s}^2 = 8{,}000 \text{ N/m}^2$$
$$= 816 \text{ kg(wt)/m}^2 = 167 \text{ lb/ft}^2$$

If it is known that the building will have an area normal to the flow A_d equal to 18 m², and C_d is 1.2, as determined by an aerodynamic study of the particular structure, then application of equation [13] gives a total normal force

$$F_d = (1.2)(18)(8{,}000) = 172{,}800 \text{ N} = 17{,}630 \text{ kg} = 38{,}880 \text{ lb}$$

If it is also known that the projected roof area A_1 equals 30 m² and C_1 is determined to be 0.5, equation [14] gives

$$F_1 = (0.5)(30)(8{,}000) = 120{,}000 \text{ N} = 12{,}240 \text{ kg} = 27{,}000 \text{ lb}$$

The magnitude of the resultant force acting on the building from powder avalanche loading is shown in figure 14. The resultant force F and the angle through which it acts is calculated by vector addition of F_1 and F_d.

The methods described here to compute forces from powder-avalanche loading do not differ from methods used to compute wind loads. Thus, engineering methods used in building design for wind loading can be freely applied in design for powder avalanches. It should be remembered that the effective bulk density of the avalanche "fluid" may be from 2 to 20 times greater than clear air density. This example assumes steady flow around the object.

Dense Flowing Avalanche Impact

When a dense mass of flowing snow impacts an object, the flow is either deflected by the object or is brought to rest against it, suffering nonrecoverable deformation and increasing the bulk density of the flowing snow to some much higher density.

If all of the snow is deflected laterally by the object, deposition and compression of snow do not occur at the object and the direction of the flow is changed by 90°.

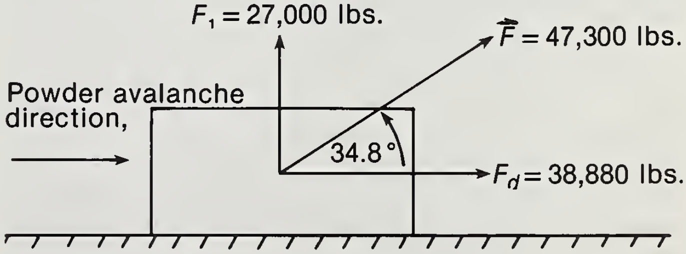


Figure 14.—Resultant force acting on a building from powder avalanche loading.

In this case, the value of K in equation [11] is 1.0, and the expression for dynamic pressure becomes

$$P = \rho' V^2 \qquad [15]$$

However, the snow from dry avalanches is typically compressed against objects to densities of 300-550 kg/m³, several times the mean bulk densities of the avalanche before impact. According to Mellor (1968), the effect of density increases upon impact can be accounted for by assuming snow behaves as a compressible plastic material. Compressibility effects are considered by assuming $K = \rho_2/(\rho_2 - \rho')$ where ρ' and ρ_2 are the respective densities before and after impact. If we assume, as a typical value, that $\rho_2 = 3\rho'$, then K equals 1.5 and the expression for dynamic pressure becomes

$$P = 1.5\rho' V^2 \qquad [16]$$

Equation [16] should be used to compute impact pressures of flowing avalanches against large, flat surfaces.

Mixed Motion Avalanche Impact

Some structures are reached by both flowing and powder avalanches during separate events or during the same event. When this is the case, designers must consider both types of impact.

DEFLECTING AND GUIDING STRUCTURES

Introduction and Terrain Considerations

Deflecting structures are intended to change the direction of flowing avalanches, thereby limiting the area of the natural runout zone. Powder avalanches are generally too deep and are of too high a velocity to be deflected; they tend to override deflecting structures. Deflecting structures have proven to be most useful in cases where an avalanche confined to a gully discharges onto an alluvial fan at the base of the gully. In such cases, uncontrolled dry-snow avalanches would tend to spread laterally across the fan. Wet-snow avalanches may assume a digitate form on an alluvial fan as each advancing finger of snow is deflected to new directions by small-scale terrain irregularities (fig. 7). An example of a broad alluvial fan upon which avalanches are known to have spread for long distances is shown in figure 13.

Although large areas can be made relatively hazard-free by carefully designed and located deflecting structures, it is necessary that planners identify the most desirable locations for the protected objects. It is possible that the runout distance may actually be increased in the direction to which the snow is deflected because the avalanche flow depth may be increased in the direction of the deflection.

Guiding and deflecting structures will be most effective on runout zone and lower-track slopes of 12-20°. On slopes steeper than 20°, dry, flowing avalanches of design size may flow at high velocities and tend to override deflecting structures. In contrast, on slopes less than approximately 12°, even large avalanches tend to deposit much of their mass. Deposition of snow against a structure reduces its effectiveness because such deposition reduces the effective height of the structure. Deposition and overtopping are serious design problems with all structures located in the lower track and runout zone including catching, retarding, and direct-protection structures. No clearcut guidelines can be given as to the optimum steepness of terrain upon which structures should be placed. The small design avalanches typical of small paths (fig. 1), will begin to decelerate and deposit debris on steeper slopes, perhaps of 15-25°. In such cases, because of lower maximum velocities, it may be possible to deflect the flow on slopes steeper than 20°. In contrast, very large design avalanches on major paths may only begin to decelerate and deposit on slopes of less than 15° (fig. 3). Thus, design-avalanche parameters must be calculated as discussed in the section on Design Criteria before defenses can be located or sized, and the expected area of avalanche deposition must be determined.

If avalanches smaller than design size frequently deposit debris against structures, it may be necessary to clean debris away periodically in order to maintain the effectiveness of the structure.

In figure 15, confined and unconfined avalanche paths are compared in terms of suitability for deflection of avalanches. It can be seen that a much greater, relative area can be protected in a confined avalanche path.

Design Height of Guiding Structures

Guiding structures are not intended to change avalanche direction, but to prevent an avalanche from spreading laterally. The required height of guiding structures depends on the flow height, cross-sectional area, and hydraulic radius of the natural avalanche. Computation of guiding-wall height is illustrated in figure 16.

Numerical Example.—(Explanation for figure 16).

Avalanche conditions:

The natural channel has a slope of 25°, a flow height of 10 m, side slopes of 45°, and cross section area of 100 m². The guide channel has a slope of 15° and a width of 20 m. Guide channel height is unknown and must be calculated. Assume coefficient of sliding friction to be 0.20.

To compute guide wall height apply the continuity equation,

$$R_l F_l^2 = \frac{(\sin \alpha_u - \mu \cos \alpha_u)}{(\sin \alpha_l - \mu \cos \alpha_l)} R_u F_u^2$$

where R_u and R_1 are the hydraulic radius of the upper and lower channels, respectively; F_u and F_1 are the cross-sectional areas of upper and lower channels,

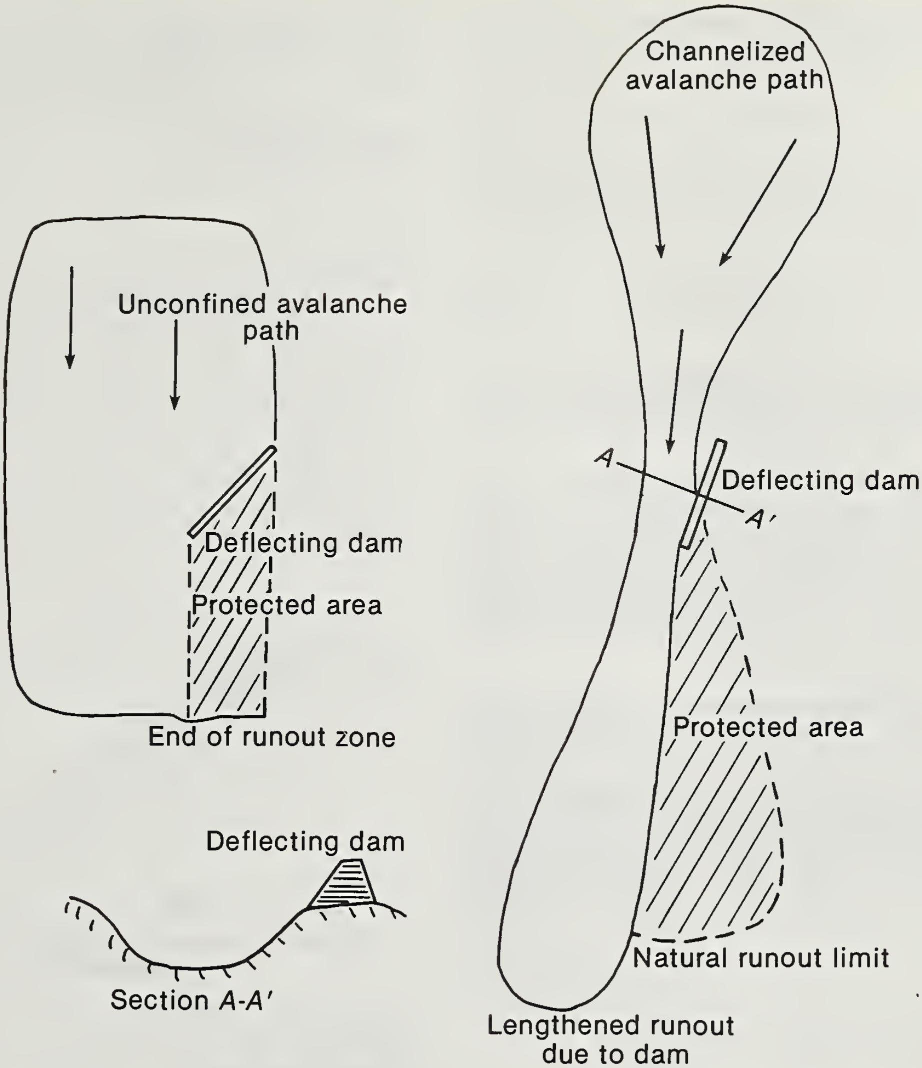


Figure 15.—Illustration of the relative effectiveness of two deflecting dams of comparable length. The dam protects a smaller area below the unconfined path. The runout zone may be lengthened as a result of deflecting the flow.

respectively; α_u and α_l are the slopes of the upper and lower channels, respectively; and μ is the coefficient of sliding friction.

Because the guiding channel is rectangular,

$$R_l F_l^2 = \frac{20h'}{2h'+20}(20h')^2$$

Thus,

$$\frac{(8{,}000h'^3)}{2h'+20} = \frac{(\sin 25° - .2\cos 25°)}{(\sin 15° - .2\cos 15°)}(R_u F_u^2) = 130{,}300$$

Solution of the above equation yields $h' = 8.4$ m, the required height of the guiding walls. Note that the hydraulic radius is equal to the channel cross-sectional area divided by the wetted perimeter.

Design of Deflecting Structures

Design alternatives consist of straight or curved structures. Either may consist of earthen dams or structural dams designed for impact. The choice of structure type depends on the shape of natural terrain irregularities and the availability of materials.

Straight Deflecting Walls

When the momentum of an avalanche is changed, as by altering the flow direction with a deflecting wall, the flow depth will increase at the object. This flow-depth increase is the climbing height h which is a function of velocity V, deflecting angle ϕ, and acceleration of gravity g. The design height H of the structure is the sum of climbing height h, flow height h', and snowpack

depth h_0. These quantities are illustrated in figure 17. Design height H is computed by

$$H = h_0 + h' + h \qquad [17]$$

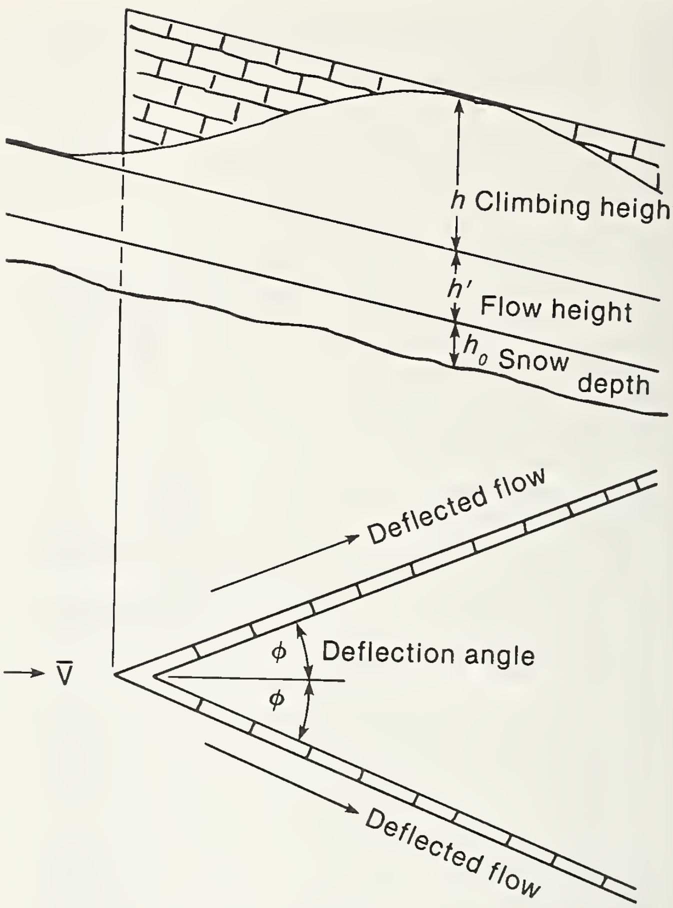
Climbing height is calculated as $h = (V \sin \phi)^2/2g$. Thus, equation [17] becomes

$$H = h_0 + h' + (V \sin \phi)^2/2g \qquad [18]$$

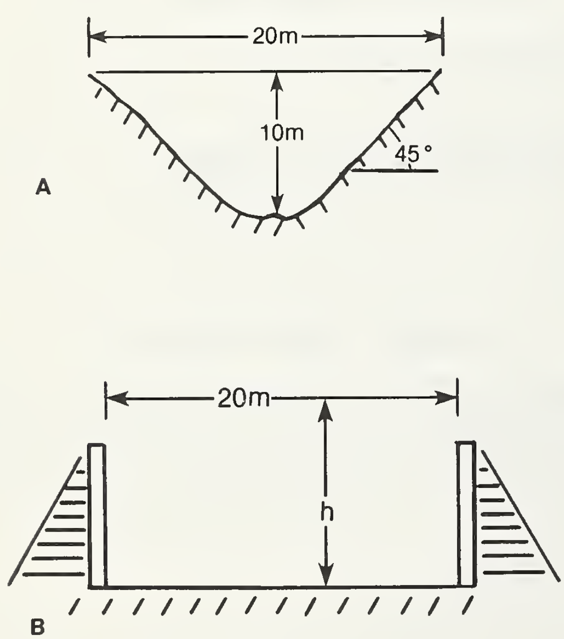
When ϕ is zero, there is no deflection and the wall behaves as a guiding wall. If ϕ equals 90°, the wall acts as a dam or a catching structure.

The design height increases rapidly with both velocity and deflecting angle; consequently, it is often recommended that ϕ be kept as small as possible. Consider, for example, a design avalanche with the following characteristics: $V = 25$ m/s, $h' = 2.0$ m, $h_0 = 1.0$ m, and $\phi = 15°$. In this case, $H = 4.74$ m, but if ϕ is increased to 30°, then H increases to 10.97 m.

Deflection forces result when the momentum of an avalanche is changed by an object. The following discussion of deflection forces is applicable to vertical structural walls and to the splitting-wedge type of direction-protection structure (discussed further in the section on Direct Protection Structures). Earthen structures need not be designed for deflecting forces because of their large mass. The magnitude of the deflection force depends on the avalanche velocity and density, the deflection angle ϕ and the area of the impact surface. These quantities are illustrated in figure 18.



Figures 17.—Design height of a deflection wall (or wedge). Design height, $H = h_0 + h' + h$.



Figures 16.—Dimensions of guiding structure. (A) Natural avalanche channel above guiding structure, (B) Cross section view of guiding structure.

The specific deflection force (i.e., the force per unit area of impacted surface) can be defined in terms of three mutually perpendicular components: normal, shear, and uplift. In the view of the uncertainties that exist regarding the details of avalanche impact (see Avalanche Impact section), it should be assumed that $0.5P_n = P_s = P_v$, where P_n is the normal pressure, P_s is shear, and P_v is uplift. The normal pressure P_n is calculated as

$$P_n = \rho'(V \sin \phi)^2 \qquad [19]$$

where ρ' is the avalanche density. Thus, for $\phi = 90°$, $P_n = \rho' V^2$, the expression for fluid impact on a large, flat surface normal to the flow direction.

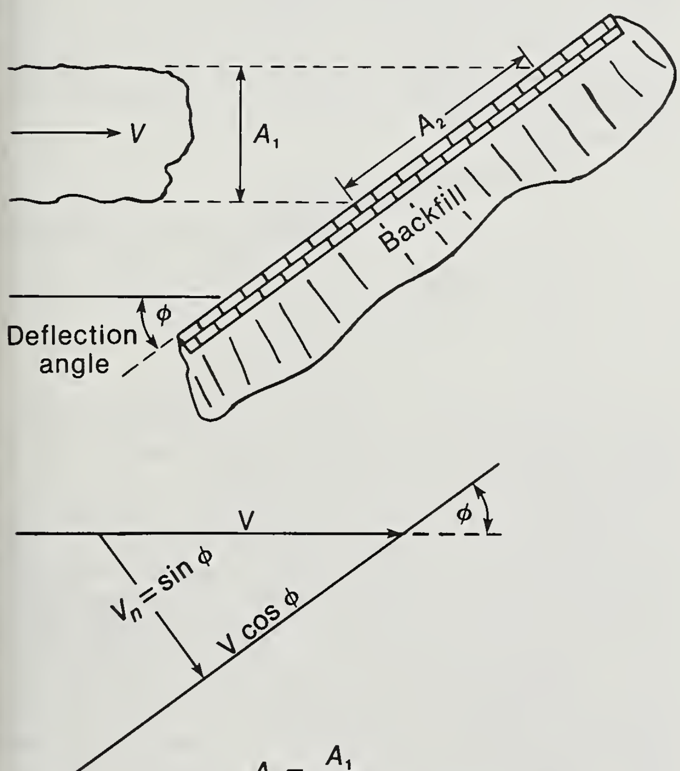
The total dynamic force on a wall is equal to the summation of all specific deflection forces times the areas over which these specific forces act. As illustrated in figure 18, an entire wall will not be affected by impact because some finite distance is required before the

avalanche can reach maximum height. Because this distance is unknown, it should be assumed that the impact area is equal to the design height times the length of the wall.

The total normal force F_n per unit length of wall is

$$F_n = P_n H + \rho g H^2/2 \qquad [20]$$

where $\rho g H^2/2$ is the "hydrostatic" force per unit length of wall. This expression for "hydrostatic" force is an overestimate because it does not take the shear strength of the snow into account, but, because shear strength varies considerably and cannot be estimated in advance, the simple expression given in equation [20], which assumes zero shear strength, should be used in design. Figure 19 illustrates the locations of resultants of the dynamic and static normal forces on a flat, vertical wall.



$$A_2 = \frac{A_1}{\sin\phi}$$

Normal Pressure: $\rho' V_n^2$

$$P_n = \rho'(V \sin\phi)^2$$

Deflection force:

$$F^2 = P_n A_2 = \frac{\rho' V_2 \sin^2\phi A_1}{\sin\phi}$$
$$= (\rho' V^2 \sin\phi) A_1$$

Shear: $P_n \mu$

Figures 18.—Deflection wall: forces and unit forces. V = Avalanche velocity, A_1 = Cross-section of avalanche front, A_2 = Area or impact surface on wall.

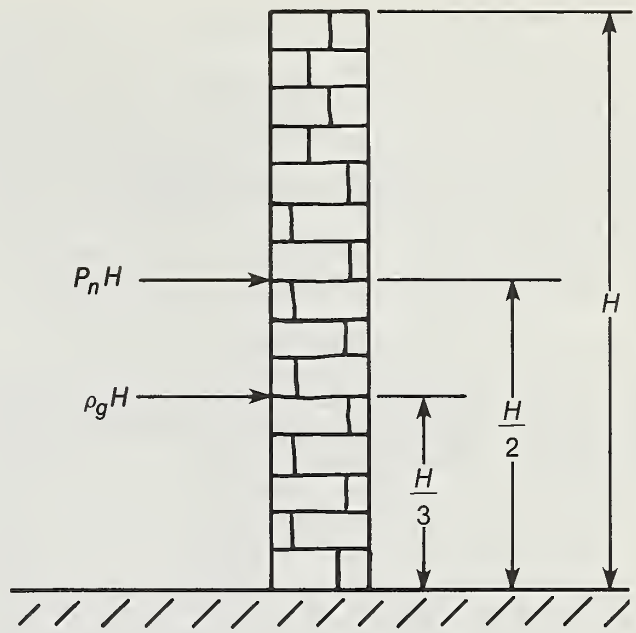


Figure 19.—The location of the resultants of the normal forces on a flat, vertical wall.

Numerical Example.—Compute the forces acting per unit length on a wall deviating 30° from the avalanche flow direction (ϕ = 30°). The design-avalanche characteristics at the wall location are: $V = 20$ m/s, ρ' = 200 kg/m³, and $h' = 1.0$ m. The snowpack depth, h_0, can be assumed to be 0.5 m.

From equation [18],

$$H = 0.5 + 1.0 + 20(0.5)^2/19.6 = 6.6 \text{ m}$$

thus, the required wall height is 6.6 m. The normal pressure from equation [19] is

$$P_n = 200[(20)(0.5)]^2 = 20{,}000 \text{ N/m}^2$$

and $P_v = P_s = 10{,}000$ N/m². The average "hydrostatic" force per unit length of structure is

$$\rho g H^2/2 = \frac{200(9.8)(6.6)^2}{2} = 42{,}700 \text{ N/m}$$

thus, the total normal force per unit length (eq. [20]) of structure wall equals

$$F_n = P_n H + \rho g H^2/2 = 20{,}000(6.6) + 42{,}700 = 175{,}000 \text{ N/m}$$
$$= 17{,}800 \text{ kg/m} = 12{,}000 \text{ lb/ft}$$

$$F_v = (P_n/2)H = 10{,}000(6.6) = 66{,}000 \text{ N/m}$$
$$= 6{,}730 \text{ kg/m} = 4{,}530 \text{ lb/ft}$$

$$F_s = (P_n/2)H = 10{,}000(6.6) = 66{,}000 \text{ N/m}$$
$$= 6{,}730 \text{ kg/m} = 4{,}530 \text{ lb/ft}$$

Curved Deflecting Walls

A curved deflecting wall is desirable in cases where it is necessary to gradually change the direction of an avalanche. In some cases, such as near the top of some alluvial fans, the natural terrain irregularities, including channels and debris-flow levees, may favor this type of construction.

The design height of a curved wall, as with a straight wall, is computed as

$$H = h_0 + h' + h$$

where all terms are defined as in equation [17]. However, for the curved wall, the climbing height, $h, = V^2W/gR$ and the equation becomes

$$H = h_0 + h' + \frac{V^2W}{gR} \qquad [21]$$

where W is the width of the avalanche in the artificially curved section of the channel and R is the radius of curvature of this section. These quantities are further illustrated in figure 20.

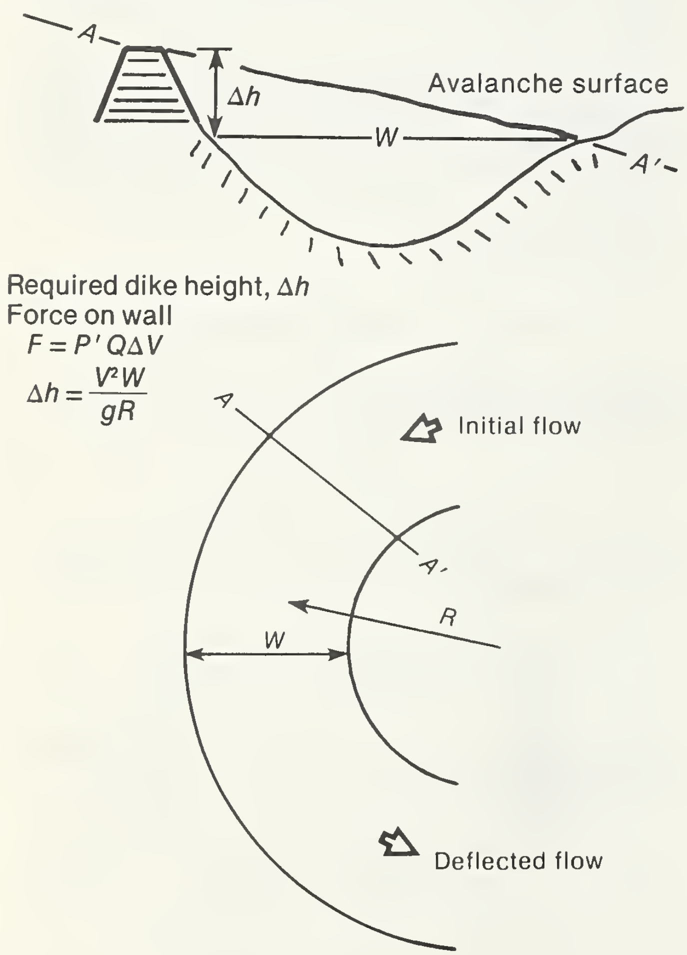


Figure 20.—Nomenclature and parameters needed to calculate dimensions of a curved deflecting wall.

The magnitude and direction of dynamic forces on the curved deflecting-wall surface are illustrated in figure 21, where the quantity Q is the design-avalanche discharge (see Design Criteria section for a discussion of Q). The x and y components of the dynamic deflection force F_x and F_y are computed based on a coordinant system as shown in figure 21. The deflection force F is equal to the vector addition of F_x and F_y, thus,

$$\overline{F} = (F_x^2 + F_y^2)^{1/2} \qquad [22]$$

where

$$F_x = \rho' Q(V_{2_x} - V_{1_x}) \qquad [23]$$

and

$$F_y = \rho' Q(V_{2_y} - V_{1_y}) \qquad [24]$$

The various velocity components used in these calculations are defined in terms of the initial avalanche velocity as it reaches the deflecting structure V_1, and the velocity as the avalanche leaves the structure V_2. For practical purposes, it may be assumed that V_1 equals V_2 whenever the wall length is short compared to the runout distance. The velocity components are defined as

$$V_{2_x} = V_1 \cos \delta$$

$$V_{1_x} = V_1 \cos 0° = V_1$$

$$V_{2_y} = V_2 \sin \delta$$

$$V_{1_y} = V_1 \sin 0° = 0$$

The angle δ, as defined in figure 21, is equal to the maximum change in the avalanche flow direction as a result of deflection by the curved wall.

It should be remembered that these equations are borrowed directly from fluid dynamics and assume the snow avalanche is a moving field. Forces are computed by calculating momentum change in a fluid. In a real avalanche, we may expect the behavior to differ from that of a true fluid at the structure. Frictional forces are activated upon impact and snow will tend to be deposited against the structure. The discharge Q, therefore, will decrease with distance along the structure, especially if the structure is located near the bottom of the runout zone in an area of low gradient. As discussed previously, the meaning of low gradient varies for avalanche sizes and types.

In addition to the dynamic forces illustrated and discussed, a normal "hydrostatic" force also exists and is equal to

$$\left(\frac{\rho g H^2}{2}\right) L \qquad [25]$$

where L is the length of the wall. The total force on the curved wall surface is equal to the vector summation of the hydrostatic force and the dynamic deflection force.

Numerical Example.—Compute the resultant dynamic force and the 'hydrostatic" force on a curved deflecting wall surface. The design avalanche characteristics at the structure are: $V_1 = 25$ m/s, $W = 10$ m, $h_0 = 0.5$ m, $h' = 2.0$ m, $\rho = 200$ kg/m³, and $Q = 1{,}000$ m³/s. The deflection wall has a radius of curvature R of 100 m; $\delta = 20°$.

From equation [21], the design height is

$$H = 0.5 + 2.0 + 6.25 = 8.7 \text{ m}$$

The dynamic force (fig. 21 and eq. [22]) equals

$$\begin{aligned}\overline{F} &= \{[200{,}000(25 \cos 20° - 25)]^2 \\ &\quad + [200{,}000(25 \sin 20° - 0)]^2\}^{1/2} \\ &= 1{,}740{,}000 \text{ N} = 177{,}000 \text{ kg} = 391{,}000 \text{ lb}\end{aligned}$$

The "hydrostatic" force, from equation [25], equals

$$\begin{aligned}\frac{200(9.8)(8.75)^2}{2}\,34.9 &= 2{,}619{,}000 \text{ N} \\ &= 267{,}200 \text{ kg} = 589{,}200 \text{ lb}\end{aligned}$$

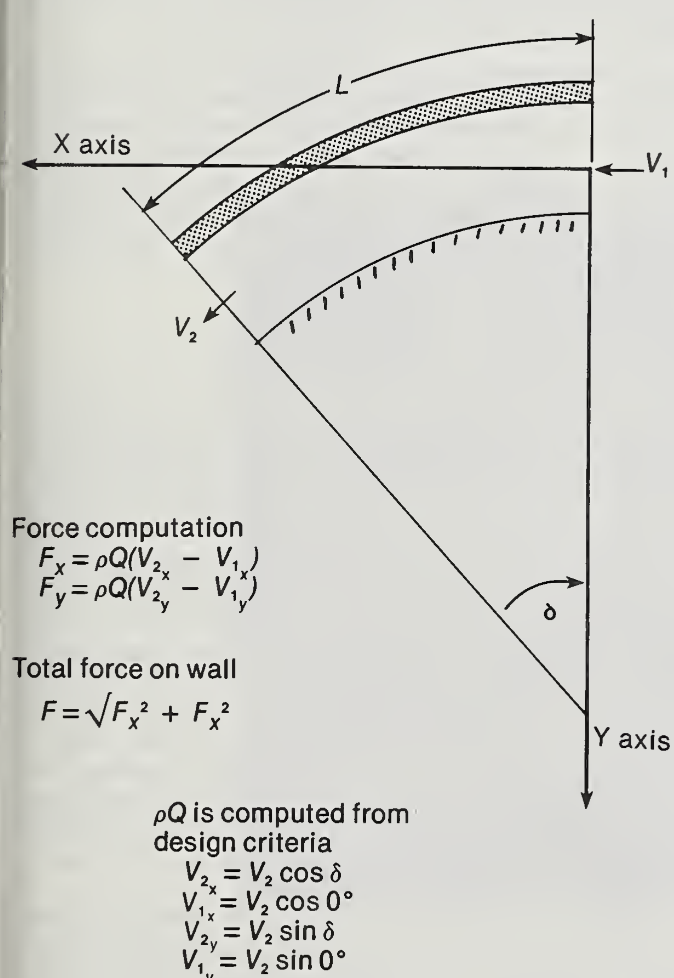


Figure 21.—Computation of total force on a wall.

Wall length L is computed as

$$L = (\delta/360)(2\pi R) \qquad [26]$$

Therefore, in this example,

$$L = (20/360)[(2)(3.14)(100)] = 34.9 \text{ m}$$

Volume and Cost of Earthen Deflecting Walls

It will often be true that earthen deflecting walls will be more economical than structural walls. The cost of earthen walls is mainly a function of the amount of unconsolidated material that must be moved during construction; thus, it is important to be able to relate wall volume required to protect a given area to the deflection angle. It is recognized that the same area can be protected by a short, high wall with a high deflection angle as can be protected by a long, low wall using a low deflection angle, but space available is usually the principal consideration.

Dimensional analysis shows that, for a given width of protected area and a given avalanche velocity at the defense structure, the required earthen structure volume increases in proportion to $(\sin \phi)^3$. The relative volume of a structure is shown as a function of ϕ in figure 22. Figure 22 demonstrates the sensitivity of volume to deflection angle, especially in the range of $20° \leqslant \phi \leqslant 50°$. For example, an increase in ϕ from 30° to 50° requires a 3.5-fold increase in wall volume.

CATCHING STRUCTURES

Purpose

Catching structures are intended to stop flowing avalanches and the lower portions of mixed motion and powder avalanches, thereby defining the lower limit of the design avalanche. Where mixed motion and powder avalanches are the design case, it may be possible to stop most of the avalanche mass behind a catching structure, allowing the more diffuse, low-density, powder portion to overtop the structure and continue into the runout zone. If powder avalanches are expected to continue into the runout zone, exposed structures below the catching structure should be designed for powder avalanche impact (see sections on Avalanche Impact and Direct Protection Structures). There is a possibility that a powder avalanche will be deflected upward by a catching structure, causing the impact to be down upon the top of exposed structures farther into the runout zone. This possibility should be carefully avoided through design.

As subsequent discussion will show, it is not practical to completely stop high-velocity avalanches regardless of the type. Thus, avalanche velocity and flow height are the controlling factors in assessing design feasibility and must be determined prior to design, as discussed in the Design Criteria section.

Terrain Considerations

Field observations of avalanche-debris distribution suggest that large avalanches begin to deposit debris and decelerate on slopes of less than 15-20°. Thus, catching structures will generally be more effective on slopes of less than 20° where avalanches lose energy naturally. If the design avalanche has very high velocity and great flow height, catching structures should be placed only on slopes of less than 15°. These reduced slopes are found not only in most runout zones but also higher in the avalanche track at breaks in slope.

Construction of catching structures in the track must be approached with caution. Construction locations often may be reached by small to medium sized avalanches of much less than design size. If this happens often enough during a given winter, catching structures may become backfilled with snow and their effectiveness will be reduced because the effective height of the structure will become less. If small slides are frequent enough, the structures intended to stop large avalanches may become completely filled with snow and can serve as ramps off of which high-velocity avalanches may become airborne. This could increase the runout-zone length.

If the runout zone is long and of moderate gradient, large avalanches will decelerate gradually. Catching dams should be located far into the runout zone where reduced velocity is anticipated and where smaller avalanches seldom penetrate.

Structure height can be determined given the design-avalanche velocity V, flow height h' and the snowpack depth at the structure h_0. The design height H of a vertical structure is determined from the expression

$$H = h_0 + h' + V^2/2g \qquad [27]$$

where g is the gravitational acceleration. Equation [27] is very sensitive to avalanche velocity and provides an

Figure 22.—Volume as a function of deflecting angle for an earthen dam. (Assumes volume is proportional to $\sin \phi^3$.)

upper limit for design height. For earthen structures with side slopes of θ degrees, the expression for design height becomes

$$H = h_0 + h' + V^2/2g(1 + \mu \cot \theta) \qquad [28]$$

where μ is the coefficient of friction between the avalanche and the structure. Assuming $\mu = 0.4$ and side slopes of 1.5:1 ($\theta = 33.7°$), equation [28] becomes

$$H = h_0 + h' + V^2/3.2g \qquad [29]$$

Equations [28] and [29] give smaller estimates of H than equation [27] because it is assumed that some of the avalanche energy is consumed as frictional work as the avalanche slides up the sloping face of the catching dam. Application of equation [29] shows how the required dam height becomes very large even for moderate avalanche velocities. For example, when $h_0 = 1.0$ m, $h' = 1.5$ m, and $V = 20$ m/s, the design height from equation [29] is 15.2 m. This shows quantitatively why it is impractical to stop large, fast-moving avalanches with a catching dam (figs. 23, 24).

The forces on a vertical, structural catching dam can be calculated by the methods given in the section on Avalanche Impact. It should be assumed that all of the snow is either stopped or is deflected through 90°; thus, the expression for normal pressure applies and $P_n = \rho' V^2$. Uplift forces will also occur against the wall and is manifested as vertical shear P_v per unit area. P_v should be assumed equal to $0.5P_n$.

Snow Storage Volume

Regardless of the adequacy of dam height, sufficient storage volume for the compressed avalanche snow must be provided behind the dam (fig. 25). If sufficient storage volume is not provided, avalanches can quickly fill in behind the dam. The mass of snow deposited behind the dam in a single design-avalanche event should be assumed equal to the mass released in the starting zone during the design avalanche (see Design Criteria section). It should also be assumed that $\rho_1 = 2\rho_0$, where ρ_1 equals the mean density of the avalanche deposit, and ρ_0 equals the mean density of the snowpack involved in the design avalanche. Thus, a maximum estimate of the necessary snow-storage volume is equal to half the volume of the starting zone. This is an overestimate because some of the avalanching snow will be deposited in the track above the catching structure.

However, as previously discussed, more than one avalanche may reach the storage area during a single winter, requiring that additional volume be provided for storage. The past history of avalanches at a given site must be determined in order to estimate avalanche frequency and to assess the reliability of a catching structure.

Figure 23.—This catching dam is built perpendicular to the flow of a large avalanche but is only 5 m high. An avalanche moving only 10-15 m/s would be able to overtop this structure. (Bethel Avalanche, near Silver Plume, Colo.)

Figure 24.—This catching dam is 20 m high and, according to equation [28], will stop an avalanche with a velocity of 22-25 m/s. Sufficient snow-storage volume is provided to stop a large avalanche. In spite of the large size of this catching dam, design engineers recognize that large, powder avalanches will easily overtop the dam. However, the nearest buildings are 500 m farther into the runout zone. (Innsbruck, Austria)

Reduction of Velocity and Length of Runout Zone

The forward velocity of an avalanche will be reduced even if the dam is overtopped because some of the kinetic energy of the avalanche is consumed in climbing the dam (fig. 23). It may be assumed that an equivalent amount of energy is not regained as the avalanche descends the downhill side of the dam because, in general, the downhill slope of the dam face will not be long enough or steep enough to permit significant acceleration of the avalanche.

The velocity reduction ΔV may be computed

$$\Delta V = [2g(H - h_0)(1 + \mu \cot \theta)]^{1/2} \qquad [30]$$

where H equals dam height, h_0 equals snowpack height (or height of previous avalanche deposits), μ equals the coefficient of friction between the avalanche and the dam, and θ equals the slope angle of the dam face. Assuming μ equals 0.4, and a side slope of 1.5:1 ($\theta = 33.7°$) for an earth-filled dam, equation [30] simplifies to

$$\Delta V = \sqrt{3.2g(H - h_0)} \qquad [31]$$

Calculation according to equations [30] or [31] enables a readjustment of the computed avalanche runout distance by use of equations [3] or [4]. The avalanche flow height may not be reduced even though velocity reduction takes place.

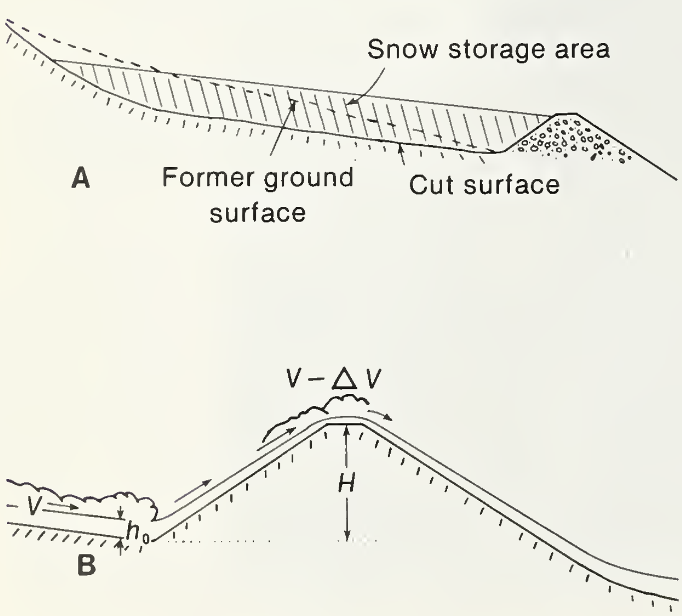


Figure 25.—Catching dams should be placed on slopes with gradients of less than 15-20° for maximum effectiveness. Sufficient storage volume should be provided to accommodate the debris from the design avalanche. (A) Relationship of dam to snow storage area, (B) Design height and velocity reduction.

Numerical Example.—A design avalanche has a computed velocity of 25 m/s and a flow height of 2.0 m. The snowpack depth is 1.0 m. A catching dam 10 m high with 1-1/2:1 side slopes is placed across the flow just above a runout zone of 8° inclination. It is assumed that μ equals 0.4 on the dam face. What will be the reduction in velocity and runout distance as a result of the dam?

From equation [31], the velocity reduction is

$$\Delta V = \sqrt{(3.2)(9.8)(10 - 1)} = 16.8 \text{ m/s}$$

Therefore, the adjusted velocity below the dam becomes

$$V - \Delta V = 25 - 16.8 = 8.2 \text{ m/s}$$

The runout distance reduction is computed by use of equation [3]. Assuming $\xi = 600$ m/s² and $\mu = 0.2$ in both cases, and assuming a velocity of 25 m/s without the dam and 8.2 m/s below the dam, the runout distances are as tabulated below.

	Velocity	Runout distance
With dam	8.2 m/s	39 m
Without dam	25 m/s	100 m

Thus, the runout distance can be shortened by 61 m. The volume of avalanche debris deposited below the catching dam will be reduced approximately by the volume stored above the dam.

Again, very deep, high-velocity powder and dry, flowing avalanches will not be substantially reduced in velocity by catching dams. This is confirmed by field observations of avalanches that indicate high-velocity avalanches may flow up and over terrain irregularities without depositing much of the mass and possibly without significant velocity reduction. Furthermore, it is possible that catching dams can serve as launching ramps for high-velocity avalanches which, having been launched, may descend upon objects from above. Thus, dams should not be built directly above buildings or other structures when high-velocity avalanches are expected.

RETARDING STRUCTURES

Purpose

The purpose of retarding structures is to shorten the runout distance of flowing avalanches by increasing ground friction and modifying the flow characteristics of the avalanches. This is accomplished by placing flow obstructions in the avalanche path that cause lateral spreading, decrease the mean flow depth, and increase frictional resistance within the flow.

Terrain Most Suitable for Retarding Structures

Retarding structures are most effective at locations where large avalanches begin to decelerate naturally, as with deflecting and catching structures. In general, they are most effective on gradients of less than 20°, areas which often correspond to the runout zones of small to medium sized avalanches. If high-velocity, dry-snow avalanches are the design case, catching structures may not be effective on slopes steeper than 15°. Because of the high velocity and large flow depth of powder avalanches, their runout length will not be reduced significantly by retarding structures.

Because retarding structures should be able to spread the flow laterally, unconfined areas of the runout zone will be more suitable for their placement than confined areas. In confined parts of the avalanche path, basal and turbulent frictional forces can be increased, but the average flow depth will not be reduced. Because of this, it can be stated that, in general, retarding structures will not be as effective on confined avalanche paths as the same structures would be on unconfined paths.

The possible effect of avalanches smaller than design size must be considered in design, placement, and maintenance of retarding structures. These avalanches will also be stopped by the retarding structures. The deposits from these smaller slides may reduce the effective height of the structures, reduce ground and structure frictional forces, and greatly reduce the effectiveness of the defense system against the larger avalanches. If deposition from smaller avalanches is thought to be a problem, it may be necessary to remove the debris after such avalanches. Removal should be done only when avalanche hazard is low.

Types of Retarding Structures

Two types of retarding structures have been used, earthen mounds and structural breakers (figs. 26, 27). Earthen mounds are effective if properly placed and are relatively inexpensive because they are composed of locally available, unconsolidated material that can be pushed into conical piles. Earthen mounds need not be designed for avalanche impact if the soil is the sandy-gravel-boulder type often found in avalanche paths. Disadvantages include the extensive earthwork and large base area required by the mounds which may result in extensive scarring of the terrain and the difficulty of removing snow from between the mounds.

Structural avalanche breakers can be used instead of mounds. However, these structures must be designed for avalanche impact and must be sufficiently large to affect the flow of the design avalanche. Because of design and construction costs, structural breakers tend to be more expensive than earthen mounds. An important advantage of structural breakers is that extensive earthwork is not required, allowing the natural ground surface to be retained between individual structures. Structures may be placed in such a way as to enable easy access for snow removal if this becomes necessary.

Figure 26.—Earthen mounds used as retarding structures. (Matt stock avalanche near Amden, Switzerland, USDA Forest Service photo)

Design of Retarding Structures

As with other types of structural defenses in the lower track and runout zone, design of retarding structures requires knowledge of the characteristics of the design avalanche. The required design parameters include velocity, flow height, and flow density. These parameters must be calculated, as discussed in section 2, prior to the design of structures.

The design height H of structures should be equal to or greater than the sum of the design snowpack height h_0 and the avalanche flow height h'. Thus,

$$H = h_0 + h' \qquad [32]$$

High-velocity avalanches tend to overtop the uphill structures (the first reached by the avalanche), but this is not a major problem, because the combined effects of increased boundary friction and forced lateral spreading will decrease avalanche velocity downstream.

The most effective array of structures is shown in figure 28. An array of this type will tend to spread the avalanche laterally, thereby decreasing the flow depth, and to increase mean boundary friction by effectively forcing the avalanche through a series of channels.

DIRECT-PROTECTION STRUCTURES

Purpose

Direct-protection structures can be used when individual, isolated objects must be protected from avalanche impact. In many cases in the United States and Europe, this type of defense has proven to be most practical because the necessary construction can often be incorporated into the design of buildings and can also take place on private property (figs. 29, 30, 31). Although direct protection may often appear to be the simplest and most economical means of avalanche protection, it is not appropriate in all situations. When several adjacent buildings need to be protected, diverting the flow by use of certain types of direct-protection structures may actually increase the avalanche hazard by changing the runout zone to a location not normally reached by the avalanche. Care must be taken in advanced planning to avoid such complications. In general, direct protection is probably not suitable for closely spaced buildings.

Terrain Where Direct Protection is Most Suitable

As with deflecting structures, direct-protection structures are most effective on slopes of 12-20°. On steeper slopes, avalanches will generally have high velocities, and on less steep slopes they may cause deposition against the object such that their effectiveness against future avalanches is reduced. Small slope gradients will not be a problem on the lower parts of long runout zones reached infrequently by avalanches. At these locations, the probability that a second avalanche will reach the protected structure while the debris from previous avalanches is still present can usually be disregarded.

Figure 27.—Retarding structures above the army barracks near Andermatt Switzerland. (USDA Forest Service photo)

Necessity of Design Criteria

As with the other types of structures already discussed, the natural characteristics of the design avalanche must be determined prior to design of the structure. Essential information which should be determined beforehand includes type or types of avalanches reaching the defense site, avalanche velocity, flow depth, and density. This information enables design in terms of structure height and strength.

Cost of Direct-Protection Structures

Recent experience with direct-protection structures (figs. 30, 31) at Vail, Colo., provides approximate estimates for architectural and engineering costs of such structures. For example, the building shown in figure 30 has a reinforced back wall designed to withstand an impact pressure of 600 lb/ft^2 (2.9 t/m^2). Engineering and architectural fees related to the design of this wall were approximately $5,000-8,000 in 1978. This cost was shared by two families. It is interesting to note that in this particular case the additional engineering costs were only 2-4% of the total construction cost and are a much smaller percentage of the present (1979) market value of this two-family dwelling (estimated to be more than $500,000). In this particular case, the construction costs of the wall are difficult to estimate because such costs were combined with other general costs. However, as a very rough estimate, additional construction costs of direct protection did not exceed the engineering and architectural costs.

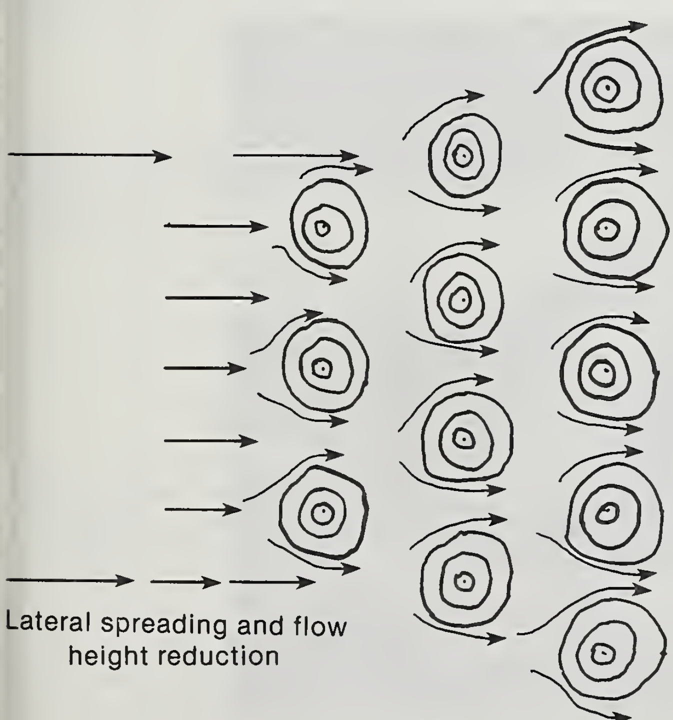


Figure 28.—This array of earthen mounds reduces the runout distance by reducing the avalanche flow depth and increasing the frictional forces between the avalanche and ground.

Figure 29.—This reinforced building wall near Davos, Switzerland, is designed to withstand avalanche impact. The wall surface is approximately normal to avalanche flow.

Design of Direct-Protection Structures

Direct-protection structures should be designed for fluid-dynamic stagnation pressures and for impact pressure from the dense, lower portion of flowing avalanches, or both. Calculation of these pressures should follow the steps outlined in the sections on Avalanche Impact and Deflecting and Guiding Structures.

In summary, the relevant equations to be used in direct-protection design are as follows:

1. The stagnation pressure when high-velocity, deep powder avalanches completely engulf an object. This is given by equation [12],

$$P_s = 1/2\rho' V^2$$

where ρ' is the bulk density of the flowing avalanche and V is avalanche velocity.

2. Impact pressure when the dense, lower portion of flowing avalanches hits a structure. This is given by equation [11],

$$P_f = K\rho' V^2$$

where $1.0 \leqslant K \leqslant 2.0$, depending on the compressibility of the design-avalanche snow upon impact.

Figure 30.—This two-family dwelling is located below a small avalanche path at Vail, Colo. (fig. 1), and is designed to withstand an impact pressure of 600 lb/ft^2 (2.9 t/m^2).

Figure 31.—This restaurant at Vail, Colo., lies within the runout zone of mixed motion and powder avalanches. The windows are artificial—the wall actually consists of reinforced concrete.

The total drag force F_d resulting from a powder avalanche that engulfs the object is calculated from equation [13].

$$F_d = C_d A_d (\rho' V^2/2)$$

and the lift force, F_l, on the same object is calculated from equation [14].

$$F_l = C_1 A_1 (\rho' V^2/2)$$

where C_d and C_1 are drag and lift coefficients, respectively, and A_d and A_1 are areas exposed normal to and parallel to the avalanche flow, respectively. These equations are discussed more fully in the section on Avalanche Impact.

The design forces on a vertical surface exposed to avalanche impact must be determined in exactly the same way as previously described for vertical, straight, deflecting walls (section on Deflecting and Guiding Structures). Design height H is computed from equation [18],

$$H = h_0 + h' + (V \sin \phi)^2/2\ g$$

where h_0 is the snowpack depth, h' is the avalanche flow depth, V is the avalanche velocity, and ϕ is the deflection angle. Normal pressure P_n is computed from equation [19],

$$P_n = \rho' (V \sin \phi)^2$$

Shear in the avalanche direction P_x and vertical shear P_v are related to normal pressure P_n by the following expression:

$$0.5 P_n = P_x = P_v$$

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Keywords: Avalanche, avalanche dynamics, avalanche control, avalanche control structures, avalanche defenses.

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U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

Great Plains

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

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